Toward an improved representation of air-sea interactions in high-resolution global ocean forecasting systems

Florian Lemarié, Guillaume Samson, Jean-Luc Redelsperger, Hervé Giordani, Gurvan Madec

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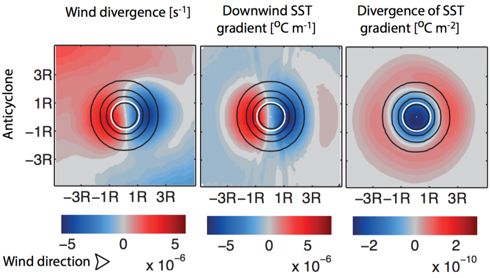
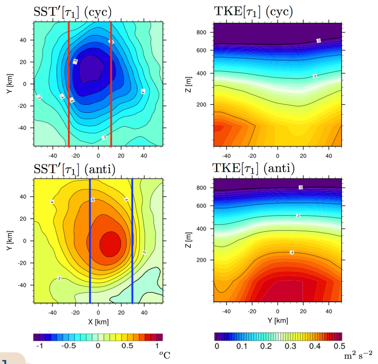
General context – Composite averaging in an eddy-centric coordinate

Eddy composites for the southern ocean from obs.



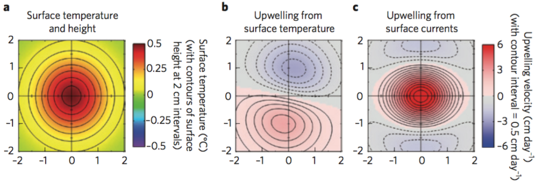
[Frenger et al., 2013]

TKE in MABL from coupled model



[Lemarié et al.]

Eddy-induced vertical velocities from obs. [Chelton, 2013]

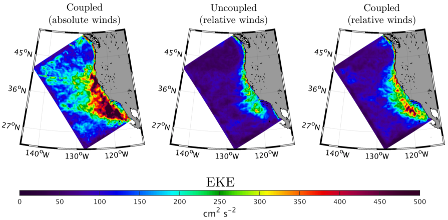


Strong thermal and dynamical coupling at the characteristic scales of the oceanic mesoscale

Limitation of current practices in global models

→ **Bulk forcing** (i.e. via an atmospheric surface-layer parameterization)

- effect of thermal coupling is <u>under-estimated</u> (no downward mixing)
- effect of dynamical coupling is <u>over-estimated</u> (wrong energy transfers)



[Renault et al., 2016]

→ **CheapAML** [Deremble et al., 2013]

- Designed for large scales (no thermal or dynamical coupling)

→ **Full-coupling**

- computationally unaffordable when $\Delta x_{\rm oce} = \Delta x_{\rm atm}$
- hard to find a good "set" of parameterizations
- Initialization issues

What are the alternatives to force an eddying global operational model (?)

Outline

1. Proposed methodology
2. Simbad1d : a simplified marine atmospheric boundary layer model
3. Atmosphere-only numerical tests
4. Coupling with an OGCM and preliminary tests

Proposed methodology

⇒ **General approach** : dynamical downscaling of atmospheric data to the oceanic resolution via a simplified MABL model (called SIMBAD) guided by operational weather forecasts or reanalysis (e.g. ERAi, operational IFS)

Momentum equation

$$\partial_t \mathbf{u} + \underbrace{\mathbf{u}\cdot\nabla\mathbf{u}}_{\text{advection}} = \underbrace{-f\mathbf{k}\times\mathbf{u}}_{\text{coriolis}} - \underbrace{\frac{1}{\rho}\nabla p}_{\text{hpg}} + \underbrace{\partial_z(K_M(z)\partial_z\mathbf{u})}_{\text{turbulent mixing}}$$

- Radiative forcing is kept as it is
- Which term should be recomputed at the resolution of the ocean ?

What is the appropriate level of complexity ...

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- ▷ Radiative forcing is kept as it is
- ▷ Which term should be recomputed at the resolution of the ocean ?

1. Derive a single-column model (SCM) (Coriolis + turbulent mixing)
2. Define a coupling between SCMs [e.g. giordani, 2006]
3. Define an integral "shallow-water like" version with slab model

Continuous formulation of single-column MABL model

Integrate winds $\mathbf{u}$, potential temperature θ and specific humidity q

$$\left\{ \begin{array}{lcl} \partial_t \mathbf{u} & = & f\mathbf{k} \times \mathbf{u} + \partial_z \left(K_m \partial_z \mathbf{u} \right) + R_{\mathrm{LS}} \\ \partial_t \theta & = & \partial_z \left(K_s \partial_z \theta \right) + \lambda_s (\theta - \theta_{\mathrm{LS}}) \\ \partial_t q & = & \partial_z \left(K_s \partial_z q \right) + \lambda_s (q - q_{\mathrm{LS}}) \end{array} \right.$$

R_{LS} represents a geostrophic "guide" and/or a Newtonian relaxation

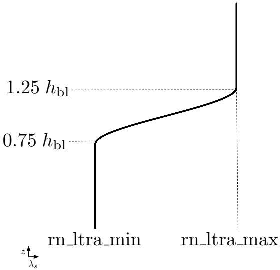
Surface boundary conditions for

$K_m \partial_z \mathbf{u}|_{z=0}, \; K_s \partial_z \theta|_{z=0}, \; K_s \partial_z q|_{z=0}$

$\rightarrow$ **IFS bulk formulation**

- used operationally at ECMWF
- consistent with large-scale data
- include sea-state and convective limit

Relaxation term scales with PBL height



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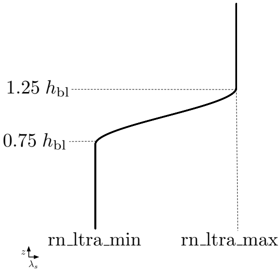


Closure scheme

TKE-based scheme following [Cuxart, Bougeault, Redelsperger, 2000]

- ▷ used operationally at Meteo-France (e.g. in Arome and Meso-NH models)
- ▷ recoded *from scratch* to allow more flexibility and better performances

$$\begin{cases} \partial_t \boldsymbol{e} &= K_m \left[(\partial_z \langle u \rangle)^2 + (\partial_z \langle v \rangle)^2 \right] - K_s N^2 + \partial_z \left(K_e \partial_z \boldsymbol{e} \right) - \dfrac{c_\varepsilon}{\boldsymbol{L}} \boldsymbol{e}^{3/2} \\ \boldsymbol{e}(z=0) &= 4.63 u_\star^2 + 0.2 w_\star^2 \end{cases}$$

$$\mathbf{K_s} = \frac{\boldsymbol{L}}{6} \phi_z \sqrt{\boldsymbol{e}}, \qquad K_e = \frac{4\boldsymbol{L}}{10} \sqrt{\boldsymbol{e}}, \qquad \mathbf{K_m} = \frac{\boldsymbol{L}}{15} \sqrt{\boldsymbol{e}}, \qquad \phi_z(z) = f(\boldsymbol{L}, N^2, \boldsymbol{e})$$

Computation of the diagnostic mixing length $\boldsymbol{L}$

At a discrete level we ensure consistency with

- MO theory in surface layer [Redelsperger et al. 2001] (i.e. $L = 2.8z$)
- [Deardorff, 1980] scale for $N^2 = \mathrm{cste}$ (i.e. $L = \sqrt{2e/N^2}$)
- [Bougeault & Lacarrere, 1989] length scale with shear-dependent term of [Rodier et al., 2017]

Evaluation of Simbad1D on standard test-case suite

→ Validation methodology along the lines of the GABLS (GEWEX Atmospheric Boundary Layer Study) initiative

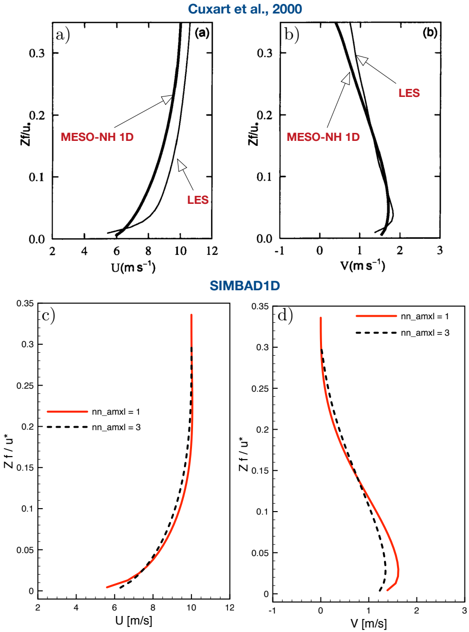
- Definition of standardized test-cases
- Model inter-comparisons between LES and SCMs

Testcases for the validation of Simbad1D

1. Neutrally stratified testcase [Andren et al., 1994]
2. GABLS1 : Stably stratified ABL [Cuxart et al., 2006] (typical situation over sea-ice)
3. Winds across a Midlatitude SST Front [Kilpatrick et al., 2014]

Simulations of reference obtained thanks to MESO-NH in LES mode

Neutrally stratified boundary layer

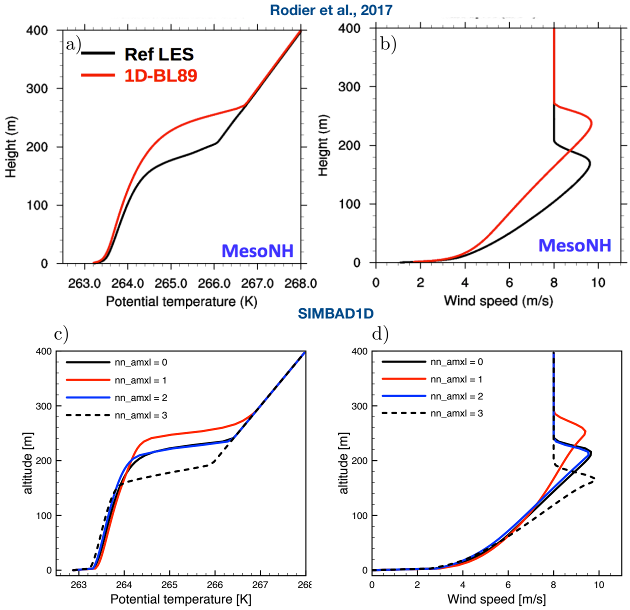


A neutral turbulent Ekman layer at 45^oN

- $(u_G, v_G) = (10, 0)$ m s^{-1}
- Roughness length of $z_o = 0.1$ m
- Simulation of 28 hours

$\rightarrow$ Improved results thanks to the discrete consistency with MO theory in surface-layer

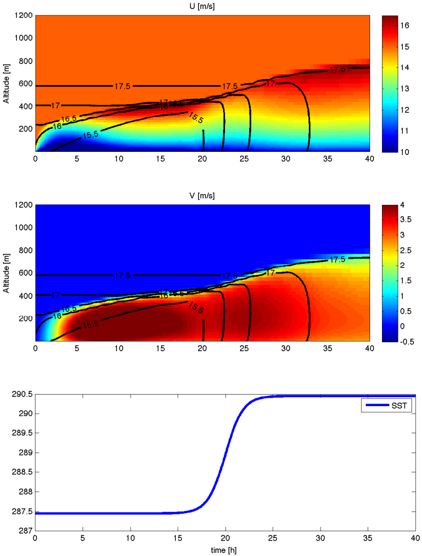
Stably stratified boundary layer (GABLS1)



- $(u_G, v_G) = (8, 0)$ m/s
- Simulation of 9 hours
- θ_s(t) = - 10^{o}C - $t/4$
- $\Delta\theta_{\rm ini} = 2^o$C

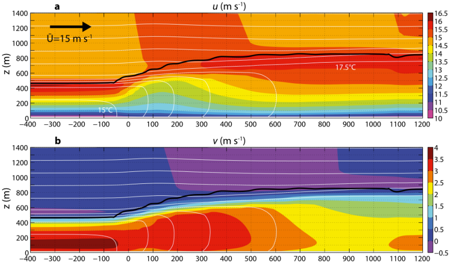
Lagrangian advection of an air column over a SST front (dry case)

SIMBAD 1D



- $(u_G, v_G) = (15, 0)$ m/s
- Cold side : $\mathrm{SST} = 14.3^o\mathrm{C}$
- Warm side : $\mathrm{SST} = 17.3^o\mathrm{C}$
- $N_v^2 = 10^{-4}\mathrm{s}^{-2}$, $\theta(z=0) = 15.8^o\mathrm{C}$
- $q(z) = 0$

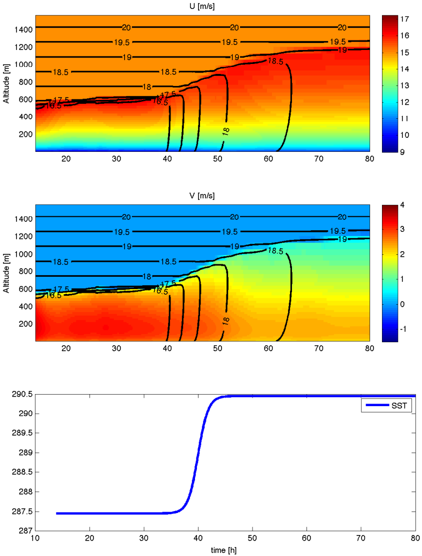
WRF [Kilpatrick et al., 2014]



2D x-z (solution at equilibrium)

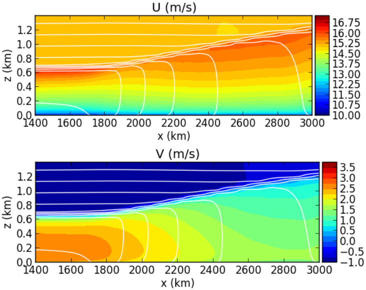
Lagrangian advection of an air column over a SST front (moist case)

SIMBAD 1D



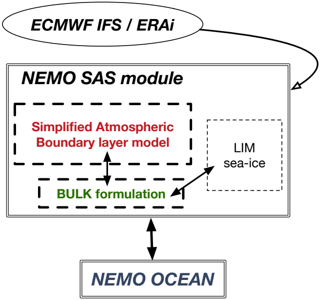
- $(u_G, v_G) = (15, 0)$ m/s
- Cold side : $\mathrm{SST} = 14.3^o\mathrm{C}$
- Warm side : $\mathrm{SST} = 17.3^o\mathrm{C}$
- $N_v^2 = 10^{-4}\mathrm{s}^{-2}$, $\theta(z=0) = 14^o\mathrm{C}$
- $q(z) = 10^{-2}\mathrm{kg\ kg}^{-1}$

MESO-NH LES



2D x-z (solution at equilibrium)

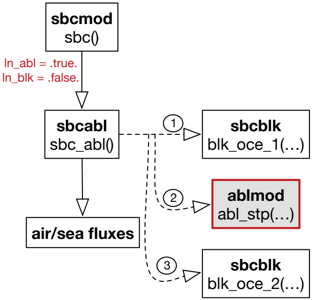
Implementation in NEMO surface module



Main developments

- Preprocessing tool to handle 3D IFS data
- Plug Simbad1D with a generic interface with the NEMO bulk routines
- Handle 3D atmospheric data instead of 2D

relatively minor modifications overall



Take advantage of existing features

- Online interpolation of external data & I/Os
- Split NEMO and SAS on separate nodes
- Bulk formulae from Aerobulk (Brodeau et al.)

Performances : a first evaluation

TOY Configuration :

- 50 x 50 points, 75 vertical levels with the default Mercator settings
- 50 vertical levels in SIMBAD1D

→ ifort with optimization options on Intel Xeon CPU E5-1650 @ 3.20GHz

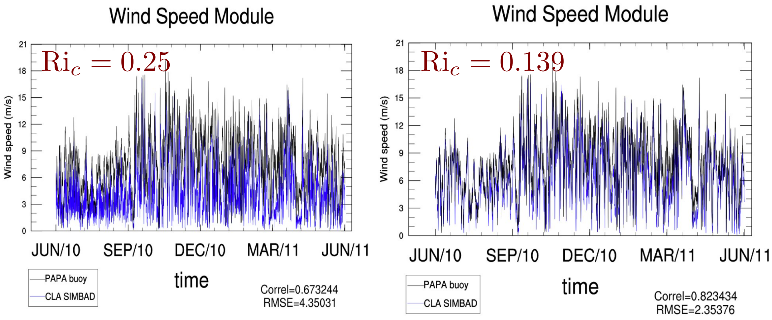
		Bulk mode		ABL mode	
module	subroutine	elapsed time	% time	elapsed time	% time
zdfgls	zdf_gls	287.52 s	19.44	287.23 s	18.06
dynspg_ts	dyn_spg_ts	166.50 s	11.26	166.67 s	10.48
traadv_tvd	nonosc	117.66 s	7.95	114.96 s	7.23
traadv_tvd	tra_adv_tvd	54.32 s	3.67	54.26 s	3.41
dynzdf_imp	dyn_zdf_imp	49.21 s	3.33	49.66 s	3.12
ablmod	**abl_stp**	-	-	**49.08** s	**3.09**
dynldf_bilap	dyn_ldf_bilap	47.44 s	3.21	47.92 s	3.01
domvvl	dom_vvl_interpol	47.34 s	3.20	47.66 s	3.00
eosbn2	rab_3d	42.74 s	2.89	42.57 s	2.68
ablmod	**abl_zdf_tke**	-	-	**49.59** s	**2.49**
trazdf_imp	tra_zdf_imp	28.42 s	1.92	28.13 s	1.77
...	...	...	...	...	...
fldread	**fld_read**	5.00 s	0.34	**10.10** s	**0.64**

Increase of memory size ≈ 12%	**24m39**	**26m30**

Ongoing work

▷ NEMO1D / SIMBAD1D coupling at the PAPA station (50.1^oN, 144.9^oW)

- Extension of the study [Reffray et al., 2015] with NEMO1d to the coupled case
- Work done by T. Brivoal & G. Samson (Mercator-Ocean)



Large-scale data from operational IFS product

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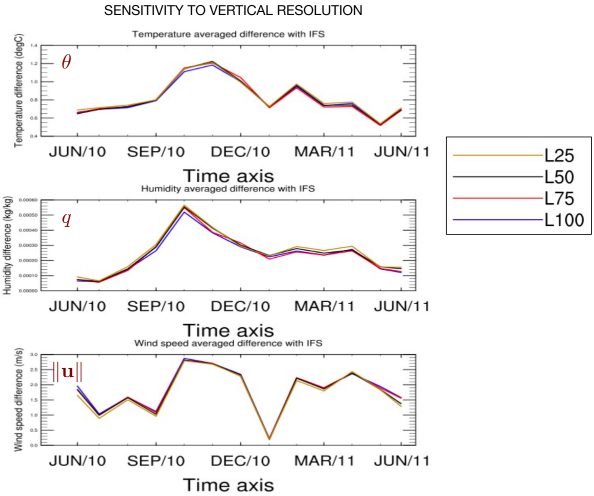

Ongoing work

- Sensitivity tests and comparison with IFS surface fluxes at global scale
- Increased level of complexity (add horizontal/vertical advection and fine-scale pressure gradient)
- Shallow-water like 2D x-y integral layer version
- SIMBAD over sea-ice
- Initialization of the NEMO/SIMBAD coupled system (in collaboration with Arthur Vidard, Inria)